

Pre-Columbian deforestation as an amplifier of drought in Mesoamerica

B. I. Cook,^{1,2} K. J. Anchukaitis,² J. O. Kaplan,³ M. J. Puma,¹ M. Kelley,¹ and D. Gueyffier⁴

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[1] Droughts in pre-Columbian Mesoamerica caused significant societal disruptions during the Late Classic and Post-Classic Periods. While the primary causes of these droughts are still debated, it has been speculated that they may be linked to extensive deforestation associated with high population densities during these intervals. Here we show that pre-Columbian deforestation would have biased the climate in Mesoamerica towards a drier mean state, amplifying drought in the region. In climate model simulations using a pre-Columbian land cover reconstruction, annual precipitation decreases by 5%–15% throughout southern Mexico and the Yucatán compared to simulations using either natural forest cover or forest regrowth associated with population declines after 1500 C.E. These changes are driven primarily by large reductions (10%–20%) in precipitation during the late summer wet season (August–September). When compared to precipitation changes estimated to have occurred during the Maya collapse, our results suggest that deforestation could account for up to sixty percent of the mean drying during this interval. Many regions previously deforested in the pre-Columbian era are now under dense forest cover, indicating potential future climate impacts should tropical deforestation of these areas accelerate. **Citation:** Cook, B. I., K. J. Anchukaitis, J. O. Kaplan, M. J. Puma, M. Kelley, and D. Gueyffier (2012), Pre-Columbian deforestation as an amplifier of drought in Mesoamerica, *Geophys. Res. Lett.*, 39, L16706, doi:10.1029/2012GL052565.

1. Introduction

[2] Severe drought almost certainly played a significant role in the disruption of the dominant civilizations in pre-Columbian Mesoamerica, including the Maya, Toltec, and Aztec Triple Alliance [Davies *et al.*, 2004; Haug *et al.*, 2003; Hodell *et al.*, 1995; Metcalfe and Davies, 2007; Stahle *et al.*, 2011; Stahle and Dean, 2011; Therrell *et al.*, 2004]. One recent study, for example, estimated that the collapse of the Maya coincided with a 25%–40% reduction in mean annual precipitation [Medina-Elizalde and Rohling, 2012]. Various hypotheses have been offered to explain the causes of these

droughts, including internal climate system variability [Hunt and Elliott, 2005], solar forcing [Hodell *et al.*, 2001], and deforestation [Oglesby *et al.*, 2010; Shaw, 2003].

[3] In Oglesby *et al.* [2010, hereinafter OG10], the authors conducted the first modeling study to explicitly test the deforestation-drought hypothesis. Using a regional model, OG10 found that complete deforestation over Mesoamerica was capable of causing a 15%–30% reduction in wet season (July) precipitation, relative to a scenario with all evergreen tropical forest cover. This drying was caused by the thermal mountain effect [Stern and Malkus, 1953], driven by reduced evapotranspiration and increased sensible heating in the deforestation case. The enhanced sensible heating increased surface air temperatures, generating rising parcels of warm air that created high pressure aloft, stabilizing the atmosphere and reducing convection and precipitation.

[4] Primary evidence for widespread pre-Columbian deforestation in Mesoamerica comes from sediment records of pollen and fire history [e.g., Binford *et al.*, 1987; Piperno, 2006]. Prior to the arrival of Europeans, Mesoamerica was likely home to over 19 million people [Dobyns, 1966; Denevan, 1992; Lovell and Lutz, 1995; Dull *et al.*, 2010], concentrated in central and southern Mexico, the Petén lowlands, and the Yucatán peninsula, where these populations converted large expanses of natural forest into agricultural land [Dull, 2008; Piperno, 2006; Whitmore and Turner, 2001; Kaplan *et al.*, 2011] (Figure 1a). Extensive deforestation began approximately 3000 years before present, becoming widespread by the start of the Common Era [Binford *et al.*, 1987]. Pollen records indicate that large-scale forest conversion for agriculture extended far beyond the centers of the major empires [e.g., Anchukaitis and Horn, 2005]. Paleocological analyses suggest the major time period of deforestation in the Maya polities of Mesoamerica occurred from the Middle Preclassic through the Late Classic, approximately 1000 B.C.E. until the 9th or 10th century C.E. [Binford *et al.*, 1987; Wahl *et al.*, 2006]. With the arrival of Europeans in the 15th and 16th centuries, indigenous populations declined by as much as 90% or more, leading to widespread land abandonment and afforestation through the time of the population nadir in the 17th century [Binford *et al.*, 1987; Dobyns, 1966; Dull *et al.*, 2010; Mueller *et al.*, 2010] (Figure 1b). Notably, the pre-Columbian pattern of land use was likely quite different compared to the modern day distribution of agricultural land (Figure 1c), with the most intensive land use in the pre-Columbian era centered around the major population centers in southern Mexico and the Yucatán peninsula. To date, however, few studies have investigated the climatic consequences of pre-Columbian land cover change, with most research focused on the carbon cycle response [e.g., Dull *et al.*, 2010; Kaplan *et al.*, 2011].

¹NASA Goddard Institute for Space Studies, New York, New York, USA.

²Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, USA.

³Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland.

⁴ONERA – The French Aerospace Lab, F-91761 Palaiseau, France.

Corresponding author: B. I. Cook, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA. (benjamin.i.cook@nasa.gov)

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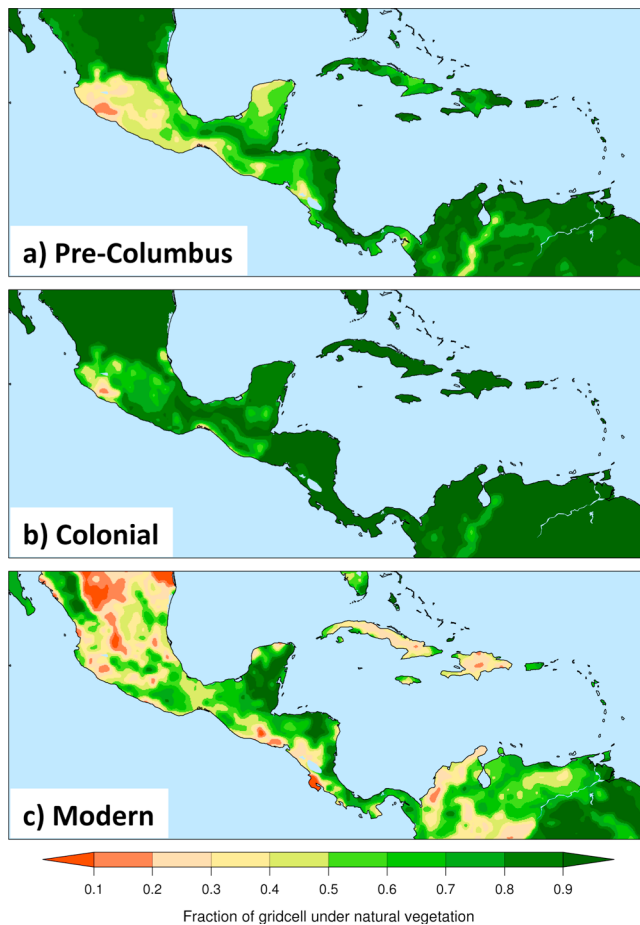


Figure 1. (a) An anthropogenic land cover reconstruction for the pre-Columbian period indicates widespread deforestation throughout southern Mexico and the Yucatán peninsula. (b) Widespread mortality following the European conquest led to as much as a 90% reduction in native populations in some regions, resulting in large scale land abandonment during the population nadir in the 16th and 17th centuries. (c) Compared to modern day land cover, pre-Columbian deforestation included much more significant forest loss in the central Yucatán.

[5] The climatic implications of pre-Columbian deforestation are intriguing but, to date, OG10 is the only study to explicitly test the deforestation-drought hypothesis in Mesoamerica. Here, we conduct a new suite of climate model experiments to investigate the impact of pre-Columbian deforestation on drought in Mesoamerica, with implications for the drying that occurred during the Maya collapse. Our work advances the study of OG10 in several important ways: 1) we use reconstructed [Kaplan *et al.*, 2011], rather than idealized, land cover scenarios in our experiments, 2) we conduct explicit significance testing, and 3) we compare our model response against precipitation changes reconstructed from paleoclimate records in the region.

2. Materials and Methods

[6] We conducted three model experiments using the Goddard Institute for Space Studies (GISS) climate model

(ModelE, 1° horizontal resolution) with the goal of isolating the equilibrium climate response to prescribed land cover boundary conditions. All experiments were run with fixed sea surface temperatures (SSTs) and sea ice concentrations (averaged over 1876–1885 C.E.) [Rayner *et al.*, 2003], as well as representative pre-industrial (1850 C.E.) climate forcings (solar, greenhouse gas concentrations, etc). The experiments were run for a total of 26 years; we allowed five years for these simulations to come to equilibrium, using the latter 21 years for our analyses. Model experiments were compared using a two sided Student's t-test, with all insignificant differences ($p > 0.05$) masked out.

[7] Each experiment is forced with a different land cover scenario, using data from the Kaplan *et al.* [2011, 2012, hereinafter KK10] anthropogenic land cover reconstruction. Our base control scenario uses natural forest and vegetation cover, with no anthropogenic land use (NATVEG). Our pre-Columbian run replaces the natural vegetation with estimates of anthropogenic land cover change, using the time period of most extensive pre-Columbian deforestation in the KK10 reconstruction (Figure 1a). DEFOREST therefore represents the epoch of maximum pre-Columbian land clearance, similar to conditions that would have existed during the Late Classic Maya Period. Comparing DEFOREST to NATVEG is our maximum effect comparison, allowing us to investigate the full potential climate response to the deforestation relative to a theoretical world with natural forest cover and no human land use. Our final experiment uses the reduced anthropogenic land cover from the Colonial population nadir (Figure 1b, REGROWTH), an interval of significant forest regrowth following Colonial-era population declines, but prior to renewed European landscape modification. The DEFOREST and REGROWTH simulations bracket the range of deforestation estimates for Mesoamerica over much of the Common Era, providing an additional comparison to examine the significance and magnitude of the climate response. Additional details on the climate model, our experiments, and land cover reconstruction can be found in auxiliary material.¹

3. Results

[8] Deforestation (DEFOREST minus NATVEG) causes significant drying in Mesoamerica, co-located with the regions of most intensive land cover change in southern Mexico and the Yucatán peninsula. Annual precipitation decreases by 5%–15% (Figure 2a); over the Yucatán and southeastern Mexico, this drying is predominately driven by larger (10%–20%) reductions in late summer wet season precipitation (August–September, Figure 2b). Precipitation changes are muted, but still significant, when the DEFOREST experiment is compared to the REGROWTH simulation (Figure S3). In this second comparison, significant drying still occurs in the core of the Yucatán peninsula (5%–10% reduction in annual precipitation), a region where the forest cover has largely recovered in the REGROWTH experiment. Outside this region, however, substantial human land use is still present (Figure 1b) and the difference in precipitation between DEFOREST and REGROWTH is small and largely insignificant.

¹Auxiliary materials are available in the HTML. doi:10.1029/2012GL052565.

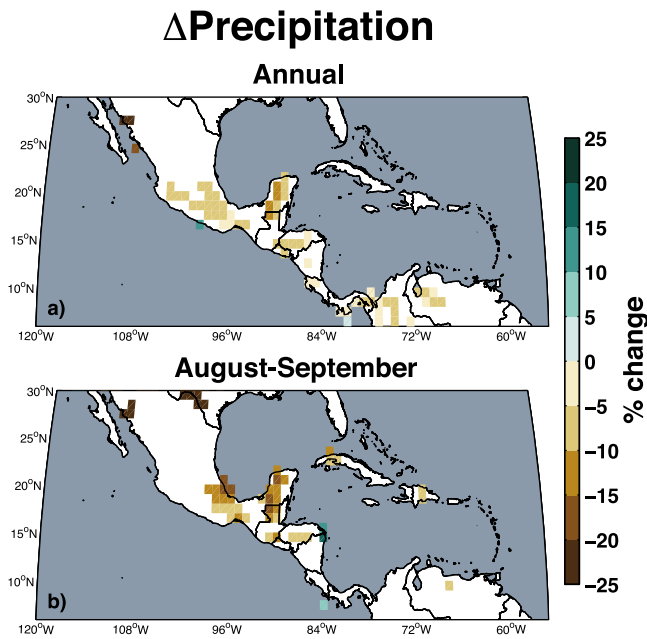


Figure 2. Percent change in precipitation in the DEFOREST model simulation, relative to NATVEG. (a) Increased deforestation reduces annual precipitation throughout much of the Yucatán and southern Mexico. (b) Over the Yucatán and south eastern Mexico, the annual decline in precipitation is driven by large reductions in late summer (August–September), up to 15%–20%. Insignificant differences (Student’s *t*-test, $p \leq 0.05$) are masked out.

[9] In contrast with OG10, the drying in our deforestation experiment is not driven by the thermal mountain effect, but rather by reductions in available energy, similar to the mechanisms first explored for the Sahel drought in the late 20th century [Charney, 1975; Charney *et al.*, 1977]. The shift from forest to crops increases the surface albedo (Figure S4a), reducing net solar radiation (Figure S4b) and net radiation at the surface (Figure 3a). The surface latent heat flux also declines (Figure 3b), driven by a combination of reduced energy availability, the shift from forests to crops with shallower roots and lower leaf area, and reductions in precipitation. Because of the net energy deficit, however, the change in latent heat flux is only partially compensated by increases in sensible heating (Figure 3c). With this radiative imbalance and reduction in latent heating, shallow convective cloud cover (below 700 hPa) is reduced over broad areas of Mesoamerica (Figure 4a) and precipitation is suppressed. Over the Yucatán peninsula, cloud cover is relatively unchanged, but the intensity of convective activity is diminished. Cloud top temperatures increase in the DEFOREST simulation over this region (Figure 4b), indicating lower elevation cloud tops, and total cloud water content is reduced (Figure 4c). Both changes are indicative of reduced convective activity consistent with the reduced precipitation (Figure 2b).

[10] Deforestation levels in pre-Columbian Mesoamerica likely fluctuated with the ascent and decline of societies and populations from the time of the Maya until the European conquest. Our DEFOREST scenario, representing peak levels of pre-Columbian population and deforestation, is an analogue for the deforestation that would have occurred

during the high population intervals, including the Late Classic Maya collapse (800 C.E.–950 C.E.). This provides an opportunity to compare our model precipitation response to empirical estimates of precipitation changes during the Maya collapse [e.g., Curtis *et al.*, 1996; Hodell *et al.*, 1995, 2005; Medina-Elizalde *et al.*, 2010]. These estimates are derived primarily from lake and cave proxies, and several of these records have been synthesized in a recent study by Medina-Elizalde and Rohling [2012], who estimated that, during the Late Classic interval, precipitation over the Yucatán was reduced by 25%–40%. Using the full range of model comparisons (DEFOREST versus NATVEG and DEFOREST versus REGROWTH), our own experiments indicate that deforestation is capable of suppressing annual precipitation over the Yucatán peninsula by 5%–15%. Our results therefore suggest that Mesoamerican deforestation may have contributed 12.5% to 60% of the total drying estimated from the paleorecords.

4. Discussion and Conclusions

[11] In their idealized (full grassland versus full forest) regional modeling study of Maya deforestation, OG10

Δ Surface Energy Balance (Annual)

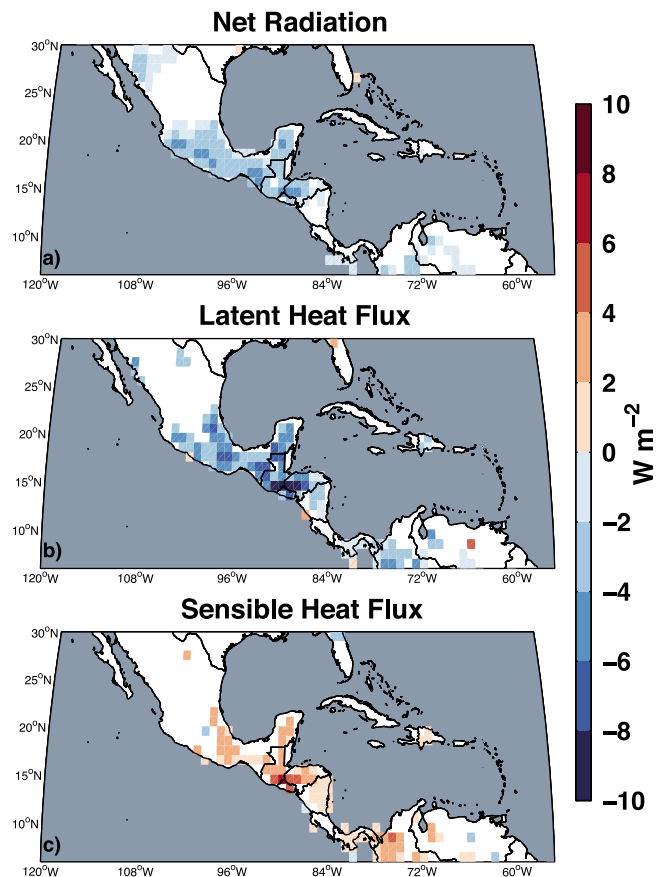


Figure 3. Increased albedo in our deforestation experiments (Figure S4) leads to a reduction (DEFOREST minus NATVEG) in (a) net radiation at the surface (W m^{-2}) and top of the atmosphere. Declines in (b) the latent heat flux (W m^{-2}) are only partially compensated by increases in (c) surface sensible heating (W m^{-2}) because of the albedo induced energy deficit.

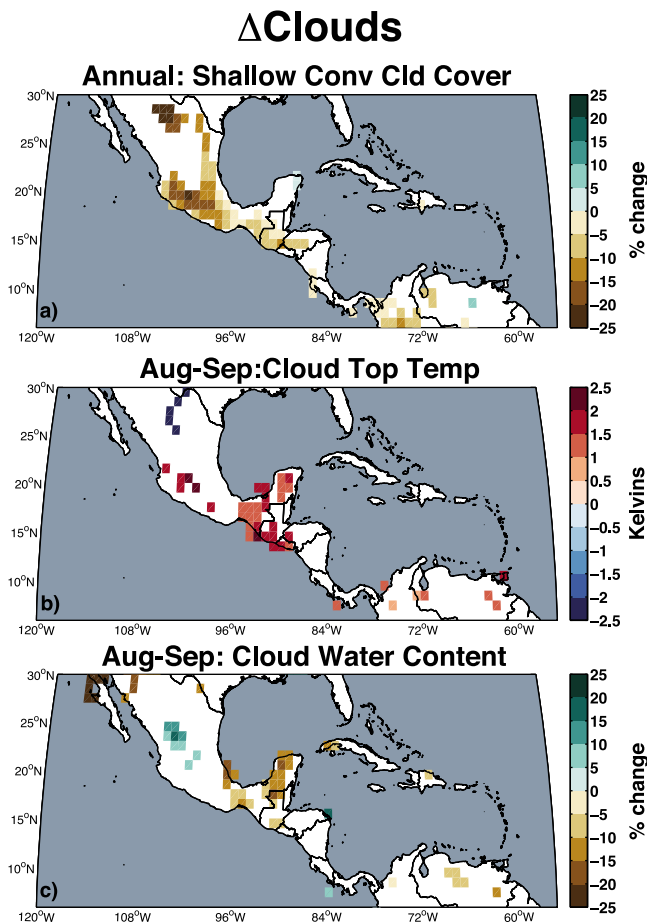


Figure 4. Changes in (a) annual convective cloud cover below 700 hPa (% change), (b) August–September cloud top temperature (Kelvins) and (c) August–September total cloud water content (% change). The energy deficit results in reduced energy available for heating and evaporation, leading to decreased convective cloud cover over much of Mesoamerica. Over the Yucatán, the drying is driven by reductions in the intensity of convection, as indicated by warmer cloud top temperatures and lower cloud water content.

reported wet season precipitation reductions of 15%–30%, although the short length of their simulations (5 years) precluded an assessment of statistical significance. Drying in our experiments was smaller but statistically significant (5%–15%), an expected result considering the much more severe deforestation scenario used in the OG10 experiments. Our study provides additional support for the general conclusions of OG10, demonstrating with a new model, new land cover scenarios, and paleoclimate data comparisons that deforestation would have contributed to the overall drying that occurred during the Maya collapse.

[12] Our results do not point to deforestation as the only or primary cause of any single, specific drought in Mesoamerica during the pre-Columbian era, and do not preclude the influence of other factors [Hodell *et al.*, 2005; Hunt and Elliott, 2005]. Nor do our simulations solve one enigma of the spatial patterns of Late Classic Maya Collapse [Dahlin, 2002], where the wetter southern lowland experienced social and political ‘collapse’ before the more arid northern Yucatán. Results from our experiments suggest, however,

that by biasing the climate to a drier mean state, deforestation in pre-Columbian Mesoamerica would have amplified those droughts when they did occur, exacerbating existing hydrologic deficits, and further contributing to climate-related instabilities and disruptions to societies in the region.

[13] In our simulations, the most severe drought in the Maya region is co-located with the dominant regional power centers of the Terminal and Postclassic. Spatial patterns of land cover and cultural change, however, were complex, asynchronous in time, and varied in magnitude [Dunning and Beach, 2000; Dahlin, 2002; Mueller *et al.*, 2010], almost certainly occurring at finer spatiotemporal scales than either our climate model or land cover reconstruction can resolve. Uncertainties also exist in the estimates of land cover change. Pollen in lake sediment cores suggest that the recovery of Mesoamerican forests following abandonment would have lasted many decades to several centuries – Mueller *et al.* [2010], for example, estimated 80 to 260 years in the Petén of Guatemala – although the timing and magnitude of deforestation and regrowth would have depended on the ecosystem and varied considerably from polity to polity [Dunning and Beach, 2000; Dahlin, 2002; Anchukaitis and Horn, 2005].

[14] Finally, we note that the modern day extent of deforestation (Figure 1c) in the region is significantly different compared to the pre-Columbian pattern (Figure 1a). This is especially true for the Yucatán where there are currently large expanses of intact forest. Our results suggest that, should deforestation in this region expand in the future, land cover change could again amplify drought in the region, a worrying prospect in light of recent, and expected future, trends towards increased aridity [e.g., Seager *et al.*, 2009; Stahle *et al.*, 2009].

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